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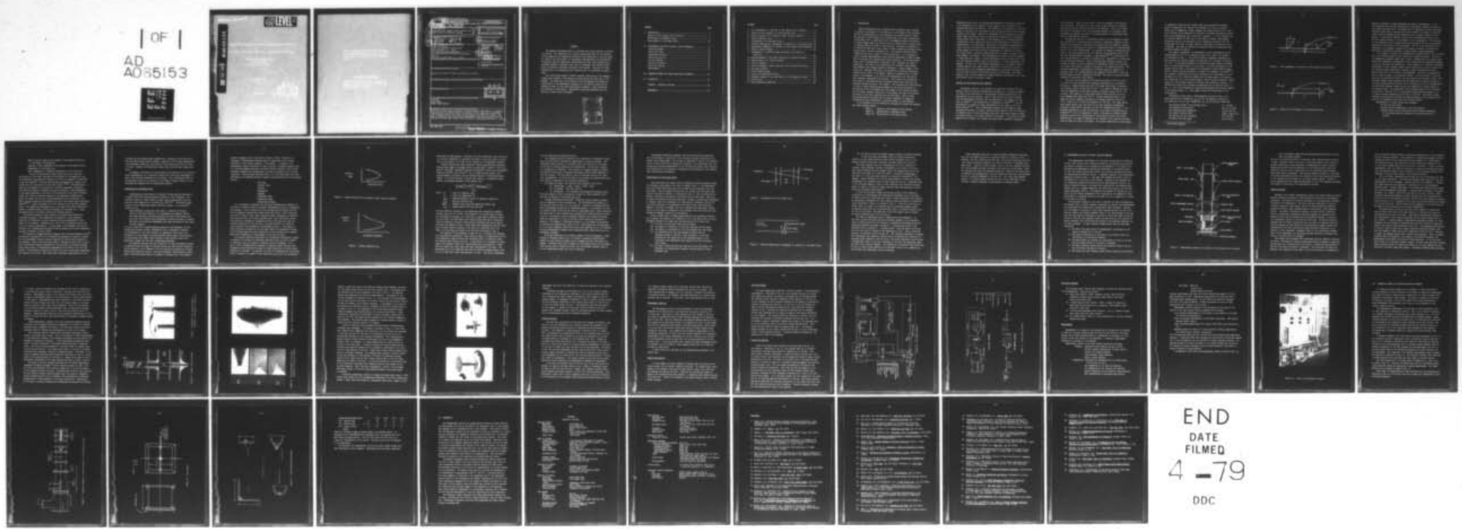

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This first annual report discusses a research project undertaken to investigate experimentally and theoretically the ignition of fuel sprays by hot surfaces and the stabilization of aircraft fires related to aircraft fire safety. The basic problems are outlined, and the experimental facilities developed for the research are described, along with a discussion of operating experience to date.

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ABSTRACT

The research discussed herein is concerned with topics related to aircraft fire safety. The objectives are to obtain experimental data for the ignition of fuel sprays by hot surfaces as affected by the properties of the fuel spray, the airflow, and the surface, to investigate experimentally the stabilization of external fires by large-scale flameholders and other flame stabilization processes related to external fires, and to investigate the combustion phenomena in partially ventilated enclosures (void spaces). Theories for these phenomena are to be extended and new theories are to be developed as appropriate.

This first Annual Report includes a general description of the research program and a summary of the research activity during the first year of the program. The first year of the research involved primarily the design and installation of the experimental equipment for the ignition study and the combustion tunnel for the flame stabilization research. These facilities are described in some detail. Experimental operating experience with the facility to date is also discussed.

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I. INTRODUCTION

These investigations are concerned with two general topics related to aircraft fire safety: (1) the ignition of fuel sprays by hot surfaces, and (2) the stabilization of both external and internal aircraft fires. The ignition of fuel sprays by hot surfaces may occur when a combustible liquid spray (fuel or hydraulic fluid, for example) caused by accidental or combat damage comes into contact with hot surfaces such as engine parts or surfaces heated by fires or other sources. The spray is dispersed in an airflow and may occur over a range of spray conditions including various droplet sizes, fraction vaporized, etc., with varying fuel/air mixture conditions, and with a range of airflow properties. It is necessary to obtain a better understanding of such ignition phenomena to enable assessment of aircraft fire hazards under those conditions. The second general topic, that of stabilization of aircraft fires, addresses two types of situations. The first is the stabilization of external fires arising from external fuel leakage caused by accidental or combat damage to fuel tanks, etc. External fires may be stabilized by structural protrusions created by the source of the damage, regions of separated flow on other parts of the airframe, or by jets of fuel penetrating into the airflow from ruptured, pressurized fuel systems. Fires within the airframe may also arise in void spaces as may be present between fuel tanks and the external airframe structure, for example. The occurrence and stabilization of fires in these confined spaces depends on the nature and extent of ventilation of the void spaces both from damage to the external airframe and the normal internal ventilation of the spaces, and also on the nature and extent of the fuel injection into the void space. Both of these flame stabilization problems must be better understood to assess the vulnerability and survivability of aircraft subject to such hazards.

It is convenient for the purposes of discussion to divide the research into three separate Phases.

Phase I. Ignition of Fuel Sprays by Hot Surfaces
Phase II. Stabilization of External Fires
Phase III. Stabilization of Void Space Fires

Experimental data are to be obtained and appropriate theoretical models are to be developed for the ignition of fuel sprays by hot surfaces in the research associated with Phase I. The effects of the properties of the fuel spray, the airflow, and the surface on the ignition phenomena will be investigated in that Phase. Phase II is concerned with the extension of experimental flame stabilization data to large-scale flameholders of double-and single-vortex types, evaluation of the applicability of existing stability correlations to the larger scale devices, and improvement of theoretical understanding of the phenomena. Both types of flameholding geometries are likely to occur in aircraft fire situations and extension of the data to scales larger than those previously investigated is essential to account for actual sizes of possible flameholding objects present in areas of structural damage, for example. The investigations of Phase II will be extended to other pertinent aspects of flame stabilization such as injection of fuel into the upstream boundary layer on the surface of a solid flameholder, for example. In Phase III, the possible stabilization of void space fires and related external fires under various conditions of ventilation and fuel injection are to be investigated experimentally and theoretical models for the flow conditions and flame stability are to be developed. The three Phases of the proposed research are being conducted concurrently, with varying topical emphasis from year to year.

Ignition of Fuel Sprays by Hot Surfaces

The general problem of the ignition of single fuel droplets and fuel sprays in air has received considerable investigation, of course, primarily by virtue of the importance of the phenomena in engine applications, and particularly for gas turbines. Most of that research has been concerned with the mechanisms associated with the vaporization and ignition of droplets in flames[1-9], the determination of flammability limits[10-17], and the determination of ignition energy requirements in fuel sprays in air with spark ignition[18-23]. While considerable progress has been made in understanding some aspects of droplet ignition, there remains a need for additional research even for those situations which have been under intensive study, as noted by Faeth in his recent review[1] of the subject. The ignition of fuel sprays by yot surfaces, by contrast, has been almost completely ignored in the literature. There has never been a thorough systematic investigation of the problem. The ignition of fuel sprays by hot surfaces is certainly among those ignition problems requiring investigation. And it is a timely one from the standpoint that the measurement methods now available, laser scattering and imaging for particle size measurement and LDV methods, make such an investigation possible.

Although the ignition of combustible mixtures by hot surfaces is generally inefficient for applications in practical combustors, research on that subject has nonetheless constituted an important part of combustion research because of its importance in studies of flammability limits in reacting gases and for fire safety applications. The ignition of stagnant reacting gas mixtures in heated enclosures and by hot surfaces within the gas (wires, rods) has been explored quite thoroughly in some instances[24-28]. The ignition of reacting gas mixtures by moving hot objects (e.g., spheres[29]) in a stationary gas has also been explored. Even for reacting gas mixtures, however, the problem of ignition by hot surfaces is an extremely complex one, involving, as it does, the catalytic effects of the wall on the reaction kinetics. One relevant experimental investigation of kerosene vapor/air ignition in a boundary layer over a heated surface was reported by Mullins[30] in 1953; the Marble-Adamson theory[31], employed by Dooley[32], was found to yield the proper parametric variations of the results.

The situation with regard to the ignition of sprays of fuel in air by hot surfaces is far inferior from either an engineering or a scientific standpoint. Studies during World War II[33] showed that sprays of kerosene would ignite within a 6-inch duct at 214 °C, for example, whereas the auto-ignition temperature for kerosene vapro/air mixtures is about 229 °C. By contrast, fuel sprays on an open heated plate yielded ignition only for plate temperatures higher than 650 °C. Another observation made in that paper was that an explosion occurred in a kerosene spray/air mixture at -23 °C, which is 65 °C below the flashpoint of the fuel. The range within which spray ignition may occur has not yet been completely established, although as noted above, some data do exist for flammability limits. It is apparently possible, as noted 30 years ago in the paper by Glendinning and Drinkwater[33], that the flammability limits of kerosene/air mixtures should properly account for the possibility of spray ignition which could extend significantly the range of flammability by comparison with vapor/air mixtures alone as shown in a plot in the paper. Yet another observation was that sprays of combustible fuels with the lowest flash points required the highest surface temperatures for ignition when sprayed on an open hot surface. These bits of fragmentary evidence suggest that spray ignition by hot surfaces certainly can be important for aircraft fire hazard analysis and should prove most enlightening from a scientific viewpoint. It is an important one for aircraft subject to fuel line or tank leaks in flight, crash damage situations, and for the penetration of an incendiary projectile into the ullage space over fuel in tanks, whereby a fuel spray is created and could be ignited. Yet there is virtually no scientific basis for assessing these potential hazards at present.

The class of problems to be represented in this investigation may be characterized by the flow of fuel/air mixture over a plane, hot surface, as illustrated in Fig. 1. The fuel/air mixture comprises a dispersion of fuel droplets with varying stages of vaporization in a laminar or turbulent air flow. For reference purposes, the turbulent boundary layers considered are to be equilibrium layers on a flat plate. The size distribution of the droplets may be taken to correspond with exponential forms normally encountered in sprays and characterized by a single size parameter, the SMD*[34,35]. The distance L identifies the induction distance to be determined in the investigation for flow velocities higher than the flame speed in the mixture. This length may not be the minimum length of heated surface required to yield ignition of the fuel/air mixture in aircraft fire situations, however. If a flameholding region were provided by terminating the hot plate as shown in Fig. 2, a fire could presumably be ignited and supported with shorter lengths of the heated surface, L*. This length is also to be determined in the investigation.

Considering a given fuel, a given material for the hot wall, and a fixed upstream wall temperature, T_{wo} (25 °C), the physical variables in the problem are the hot wall temperature, T_w, and the initial conditions:

The Reynolds number of the boundary layer	(0 - 50,000)
The pressure of the airflow	(0.2 to 1.0 atm)
The freestream gas temperature	(-20 to 200 °C)
The overall fuel/air ratio	(Equiv. Ratio $\geq$ 1)
The fraction of fuel vaporized	(0 to 100 %)
The SMD of the fuel spray	(20 to 200 μ)

* Sauter Mean Diameter.

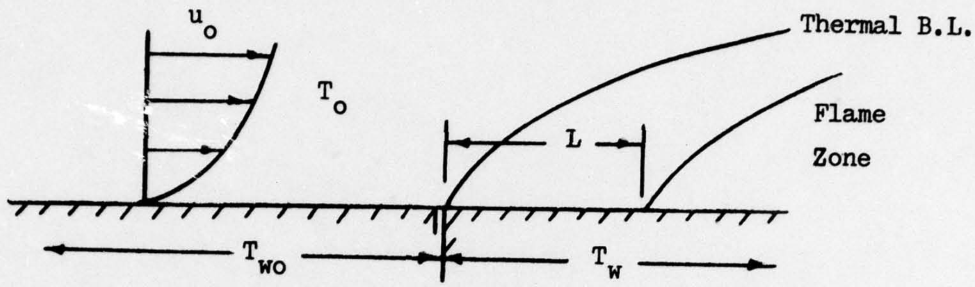

Figure 1. Flow Arrangement for Ignition of Fuel Sprays by Hot Surfaces

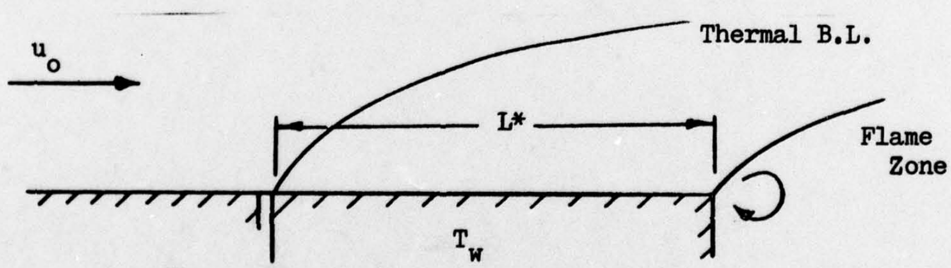

Figure 2. Ignition in the Presence of a Recirculation Zone

Ranges of interest for these parameters are given in parentheses. It can be anticipated that the wall temperatures of reasonable interest for ignition will range from about 230 ^{o}C to perhaps 1000 ^{o}C, depending on these conditions. Fuel/air mixture ratios slightly above stoichiometric are likely to yield the lowest ignition temperatures and therefore are of primary interest for fire safety. A noncatalytic material (nickel) and a representative steel alloy are the primary surfaces to be considered in the investigation. The structure of the turbulence in the boundary layers may be expected to be of considerable importance in the physics of the phenomena. This is to be controlled in the experiments; for example, attempts will be made to simulate the turbulence structure in equilibrium turbulent boundary layers in most experiments.

It is planned to conduct the investigation by employing flow in a cylindrical duct with a heated length of duct serving as the ignition source. The use of an axisymmetric geometry rather than a plane, 2-dimensional flow, greatly simplifies the experimental arrangements and the results may be reasonably extended to account for plane flow situations. A duct diameter of 2 inches is considered appropriate for this purpose; smaller ducts would conflict with the usual rule fcr minimum chamber dimensions in ignition studies (flammability tests in smaller ducts tend to be erratic and misleading). The inlet air temperature may be varied by means of an electrical heater. The exit section of the duct will also be electrically heated; the inlet section will be water cooled. The upstream boundary layer properties may be established by means of screens in the tube controlling the structure of the turbulence so as to be representative of equilibrium boundary layers and also the properties of laminar layers in the laminar regime. The properties of the boundary layers are to be measured in any event. The fuel is to be introduced by appropriate atomizers so as to produce uniform dispersions of the fuel in the flow. The fraction vaporized may be controlled by varying the upstream position of the injection station, or by introducing fuel vapor into the main airflow.

Measurements to be made include the following.

Air and fuel flow rates

Air/fuel mixture temperature at the inlet station

Boundary layer velocity distribution and turbulence parameters at the entrance and exit stations of the heated portion of the duct

SMD of the fuel spray at the entrance of the heated section and in the region of atomization

Fraction of fuel vaporized at the entrance of the heated section

Temperature of the heated wall

Mean temperature or enthalpy distribution in the flow at the exit of the heated duct under conditions close to ignition

The fraction of the spray vaporized at the entrance of the heated duct may be determined by the spillover technique of Foster and Ingebo[36], as employed by Rao and Lefebvre[37], and from existing data and appropriate theories concerned with the vaporization of such fuel sprays[1, 38-41]. The SMD measurements at the entrance of the heated duct provide independent information from which the fraction vaporized may also be estimated. Some measurements of the spray properties at the exit of the heated duct would prove extremely useful, but would be intricate because of the significant nonuniformity there; the nature and utility of such measurements will be examined. The SMD of the fuel spray may be determined by one of the current laser scattering methods[42-44]. Laser velocimetry is to be utilized for the velocity measurements. The temperature measurements are to be made with either thermocouple probes or enthalpy probes, suitably calibrated for two-phase flow. Other measurements are to be made in accord with standard practice.

The initial research on this subject is concerned with operation at atmospheric pressure. The capability for operation at lower pressures exists in our laboratory and such conditions can be accommodated in later stages of the research. Kerosene (JP-4, Jet-A) will be employed as the fuel for all of these investigations. At some stage in the research, data may be obtained for a representative alternate fuel and possibly for other combustible liquids of interest to the Air Force.

The theories of droplet ignition, together with the Marble-Adamson theory[31] and Mullins' correlation[30] will be examined and extended to attempt to account for the experimental ignition results obtained for fuel/air mists ignited by hot surfaces. Some of the results may lead to information which could be useful in evaluating transport phenomena for the particles in turbulent boundary layer flows as well, if appropriate measurements can be made at the duct exit station. The mixtures are relatively dilute ones with the gas phase dominating the dynamics of the flow. That should admit reasonable approximations to be utilized for the boundary layer computations. Pyrolysis of the fuel at the wall and other surface related effects, especially at the higher temperatures could materially complicate the situation from a theoretical point of view, of course. However, the theoretical models should provide some insight even there.

In summary, the ignition of fuel sprays by hot surfaces is to be investigated experimentally in a systematic fashion with control and measurement of each of the relevant parameters in the problem. And a theoretical model for the phenomena, based on an extension of the Marble- Adamson theory is to be developed and compared with the experimental results.

Stabilization of External Fires

Flameholding by bluff bodies in premixed, flowing fuel/air mixtures is a subject which has received extensive attention in the literature. The stability limits for flame holders of small scale in high-speed flows were explored quite extensively in the 1940s and 1950s[45-54]. The detailed mechanisms for such flameholders remain uncertain, however. As one author[55] recently put it:

> "Many parametric studies have been made to correlate the blowoff limits of such bluff bodies to the aerodynamic and chemical effects that might influence the holding process and while these studies have shown that both chemistry and aerodynamics influence holding, at present they have not yielded any unambiguous and simple mechanism for this type of flame holding."

It is not clear that a simple mechanism exists for the phenomena, but the problem does require further investigation from a fundamental viewpoint. An investigation of the scale effects on flameholders would prove most informative in that respect, and distinctions between double vortex systems (V-type gutters) and single vortex systems (L-type gutters) would offer additional insight into the basic flameholding phenomena.

In combustion parlance the term "stability" is often used rather loosely to describe either the range of fuel/air ratios over which stable combustion can be achieved, or as a measure of the air velocity the system can tolerate before flame extinction occurs. Thus the description "good stability performance" could mean either that it is capable of burning over a wide range of mixture strengths or that its blowout velocity is high. Clearly it is important to differentiate between these two properties, both of which contribute to the overall stability of the system. In general, with experimental forms of stabilizer in which the fuel is supplied premixed with air, the main emphasis has been on blowout velocity, whereas in gas turbine combustion chambers the burning range is usually considered to be of prime importance. From available stability data, it is now established that flame stabilization in premixed fuel/air streams is governed mainly by the following factors:

fuel type
fuel/air ratio
velocity
temperature
pressure
flameholder size
flameholder shape
flameholder blockage

It is customary to determine the stability performance by carrying out a series of extinction tests at constant, predetermined levels of temperature and pressure. After turning on the fuel and igniting the mixture the fuel flow is gradually reduced until flame extinction occurs. After noting the fuel and air flows at this 'weak' extinction point, combustion is re-established and the fuel flow slowly increased until 'rich' extinction occurs. This process is repeated at increasing levels of air mass flow until the complete stability loop can be drawn. The main features of a stability loop obtained by this technique is illustrated in Fig. 3. The region of stable burning is bounded by rich and weak limits which gradually converge with increasing mass flow until eventually a level of mass flow is reached beyond which combustion is unattainable at any fuel/air ratio.

The complete stability performance of a combustion stabilization scheme is obtained by carrying out sufficient extinction tests to allow a number of stability loops to be drawn at different levels of pressure. It is then a fairly straightforward procedure to translate these test data into performance charts showing the range of flight conditions over which stable combustion is possible. In practice, the risk of overheating the rig ducting tends to restrict the number of rich extinction points that can be obtained,

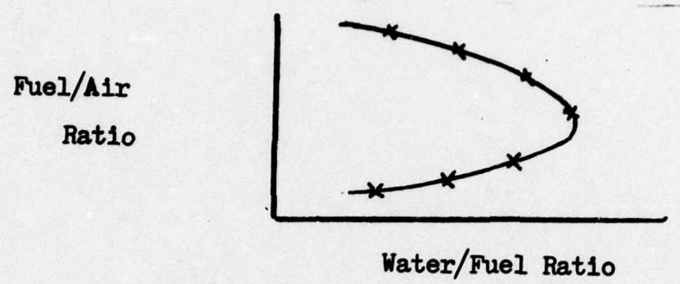

Figure 3. Typical Stability Plot (Lefebvre "Water Injection Method")

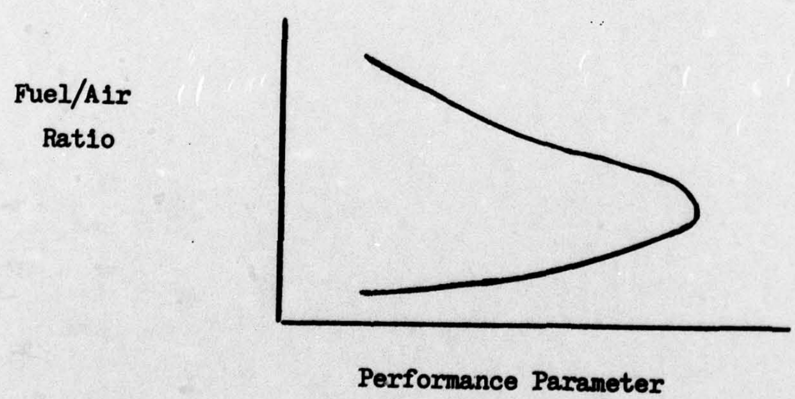

Figure 4. Typical Stability Loop

especially at high pressure. Moreover, even with large-scale test facilities it is usually impossible to determine the peaks of the loops owing to limitations on the amount of air that can be supplied at sub-atmospheric pressure.

Several theories have been proposed to describe flameholding phenomena. These include those of Williams, Hottel and Scurlock[56], Longwell, Frost and Weiss[57], Mullins[58], Spalding[59], Zukoski and Marble[60], Khitrin and Goldenberg[61], Cheng and Kovitz[62], and Loblich[63]. All of these theories account, with varying degrees of success, for the observed behavior of baffle-stabilized flames. It is found that for a second order reaction, a simplified theory yields a performance parameter of the general form

$$\frac{(P_2\, D_{ref})^m\, T_2\, \exp^{T_2/b}\, (\Delta P_{ft}/q_{ref})^{0.5\, m}}{U_{ref}}$$

where P_2 = inlet air pressure, psia

T_2 = inlet air temperature, ^oK

D_{ref} = maximum diameter or width of combustion system, in.

U_{ref} = mean air velocity, fps

ΔP_{ft} = pressure loss across the stabilizer baffle, psi

q_{ref} = dynamic head of the air flow, psi

For most practical purposes it is satisfactory and convenient to assume a constant value for 'b' of 300. The constant 'm' is on the order of unity. In the absence of blockage, as in the case of open fires, the gutter width, the wake width, the base drag of the flame holding body and the turbulence scale are expected to yield a characteristic parameter that can be used to correlate the stability limits. Where sufficient experimental data are available to permit either a portion or the whole of a stability loop to be drawn, the resulting plot should be of the type illustrated in Fig. 4.

The objective of the research in Phase II is to establish the influence of (a) geometrical parameters, namely size and shape, of flameholders and (b) flow parameters, namely velocity and turbulence scale, on stability limits for selected fuels burning with air. In particular, it is proposed to investigate the stability limits for V-type gutters and L-type gutters of sizes that are larger than those which have been investigated in the past. The experiments are to be conducted both with and without blockage effects, that is, in an "open jet" tunnel and enclosed in a duct. The initial experiments will be conducted with kerosene as fuel.

The proposed stability studies will be conducted in a combustion tunnel set up by the School of Mechanical Engineering at Purdue University. The combustion tunnel consists of a facility that can provide up to 10 lb/sec of air flow at various pressures and temperatures. The air may be heated in a preheater by combustion. The heated air is passed through a suitable contraction section and a turbulence generating section before admission to the test section. The test section, when not enclosed can be of an "open jet" configuration. On the other hand one can connect any desired duct-like test section downstream of the turbulence generators.

Utilizing the tunnel, the tentative test program is as follows.

(a) Stabilizers: 4 each, V-type; 4 each, L-type

(b) Air Speeds: 100, 200, 250 fps

(c) Turbulence: Two "standard" grid-generated turbulent flows

The total number of tests anticipated is about 50. Each stability limit map test is expected to take about two hours.

A method developed by Lefebvre[64], termed the "water injection method", will be employed for this investigation. The flameholders are placed in a 10-inch duct near its exit or in an open jet. The duct is supplied with air flow with upstream injection of a fuel/water mixture. At the start of a run, the fuel/air ratio is set and the flame is established with no water injection. The water flow is then initiated and increased until flame extinction occurs. A plot of the stability loop so obtained (fuel/air ratio versus water/fuel ratio) is equivalent to a plot of fuel/air ratio versus the reciprocal of pressure. For example, a fuel/water mixture of 1:1 by weight is equivalent to dropling the pressure by a factor of two. This method has two advantages. It is the only technique which allows the entire stability loop to be obtained and any subatmospheric pressure can be simulated while using only fan air at atmospheric pressure.

Following completion of the initial stages of this investigation, flame holders of irregular shapes are to be tested to establish characteristic lengths for such objects as might occur on damaged aircraft structures, for example. Alternate fuels may be examined in continuing efforts of the project. Other factors such as injection of fuel into the upstream boundary layer of a solid flameholding object will also be examined.

Appropriate theoretical analyses, such as those previously mentioned will be considered. Extensions of the available theories, particularly for single vortex flameholders, will be made as necessary to improve the representation of such flows from an analytical viewpoint. The theoretical work will require more detailed measurements in the recirculation region under selected run conditions for the purposes of comparison and elucidation of the possible flame stabilization mechanisms.

Stabilization of Void Space Fires

Void space fires may result when an incendiary projectile passes through the airframe, penetrating a fuel tank, as shown in Fig. 5. The pressurized fuel tank ejects liquid and vapor fuel, heated by the incendiary, into the void space. Both an external airflow and flow through the void space (ventilation flow) may be present, as indicated in Fig. 5. The void space may be sealed or partially open without ventialtion flow in some cases. There are at least two distinct situations which may be likely to arise either separately or together under such conditions: (a) there may be a transient fire in the void space resulting in overpressures there which could cause structural damage to the tank or airframe, and (b) a sustained fire may result, either within the void space or external to the airframe, fed by fuel from the tank through the passage created by the projectile.

Given a fixed amount of energy associated with the incendiary effluent in the system, the question as to whether or not a void space fire will occur presumably depends on at least the following factors for a given fuel.

(1) the rate at which fuel enters the void space,
(2) the degree of atomization of the fuel entering the void space,
(3) the degree of vaporization of the fuel entering the void space,
(4) the distribution of the total energy avialable from the incendiary vested in the air in the void space, in the fuel entering the voie space and in the incendiary matter in the void space, when significant fuel ejection into the void space first occurs,
(5) the rate at which air and fuel vapor mix in the void space, the dispersion of atomized fuel droplets, and the nature of those processes, and

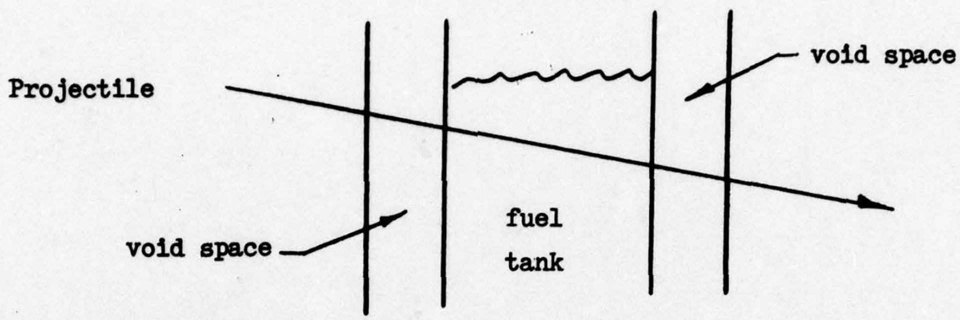

Figure 5. Configuration for Void Space Fires

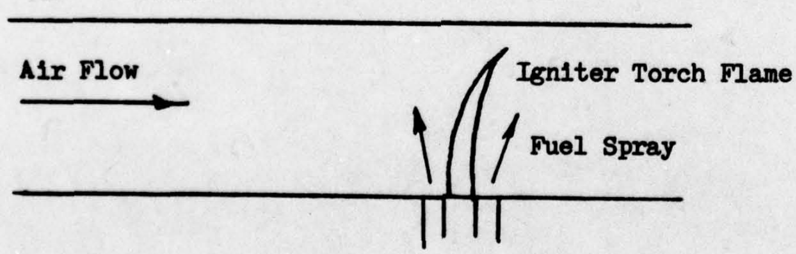

Figure 6. Tentative Experimental Arrangement for Ignition of Void Space Fires

(6) the rate at which the thermal energy initially available disperses in the void space environment from its initial distribution.

Clearly, for any actual situation, many complex processes occur, no two damage incidents resulting in precisely the same combustion situation.

The worst possible case for overpressure would be an explosion at constant volume yielding a maximum overpressure on the order of 7-8 atm. This would be reduced by flow leakage through the damaged area and by flow within the void space if it were not sealed. Transient overpressures on the order of 1-2 atm have been observed in simulation experiments,[65] for example. Ample ventilation of the void space appears to reduce the maximum overpressure for transient fires for many cases but not all. Sustained fires in the void space appear to have a lower likelihood than sustained external fires, at least in a series of tests conducted under the auspices of the Air Force Aero Propulsion Laboratory.[65]

In view of the rather complex and diverse nature of such combustion situations it is anticipated that exploratory experiments will be required to better define the conditions most likely to yield significant fire hazards. An experimental arrangement for that purpose, which may employ the combustion tunnel described in Phase II, is shown in Fig. 6. A fuel jet, which may be either vapor or a spray, is introduced into an airstream through a plate. An ignition source such as an oxy-acetylene torch, is situated coaxially with the fuel jet as shown. The upper wall of the flow channel may be located at various distances above the lower plate.

Two types of experiments may be conducted with this apparatus. In the first, plates with ports providing different degrees of flow impedance could be placed across the flow channel at upstream and downstream positions simulating partially enclosed void spaces. A limiting case would be the situation with no upstream or downstream plates. Both the igniter torch and the fuel flow would be started at the beginning of a run. After a specified duration, the igniter would be turned off. The combustion phenomena, including the overpressure and combustion duration would be observed and conditions for sustained spray combustion could be noted. The second experiment would include a flameholding object on the wall downstream of the fuel jet simulating petalled metal from projectile damage. The possibility of sustained fires stabilized by such an object either ignited by the transient torch or by a separate igniter behind the flameholder, would be explored.

These experiments may serve to define possible combustion situations both for void space fires and for external fires as a function of the geometry, the fuel condition and flow rate, the airflow conditions, and the total ignition energy provided by the torch in the case of transient void space fires. Injection of air through a port in the wall opposite the fuel jet could increase the rate of mixing of fuel and air in some cases. Since the limiting case would be completely mixed fuel vapor/air, that case could be examined by injecting such a mixture through the fuel port, with suitable screens to prevent flashback in the fuel jet. This could also simulate escape of a fuel/air mixture through the hole in the outer skin of the aircraft, possibly relulting in stabilization of external fires.

II. EXPERIMENTAL FACILITY FOR SPRAY IGNITION RESEARCH

The experimental arrangements for providing the desired flow conditions in the 2-inch circular duct comprised systems for introducing and tailoring the airflow, systems for the atomization and dispersion of the liquid fuel, provisions for measurements upstream and downstream of the heated section of pipe, the heated pipe section itself, and auxiliary systems such as that for exhausting the fuel/air mixture. A schematic diagram of the experimental apparatus is shown in Fig. 7. The basic flow channel was sized to the i.d. of Schedule 40, 2-inch pipe (2.067 inches). Starting at the upstream end, the components comprise the injector air and liquid manifold section, the main air manifold section, the liquid film trap section, the upstream measurement section, a thermal insulator, the heated pipe section, and the downstream measurement section. The apparatus is oriented for vertical flow to avoid flow and thermal asymmetries due to gravitation, as regards the spray distribution, to buoyancy effects in the gas flow, or to deposition of liquid on the walls of the duct.

The provisions needed for the flows of interest in these investigations are special ones in several respects, requiring, as they do, the establishment of the desired flow conditions in exceptionally short distances. Because the flow speeds of interest for fire safety purposes may be as low as a few feet per second, and because residence times of the liquid sprays in the flow from the time they are introduced to the time at which they enter the heated section of the duct are important insofar as they relate to the fraction of liquid vaporized, the liquid injection process is an extremely important one for these purposes. An ideal injection scheme should meet the following conditions.

1) The SMD of the spray should be independently controllable in the range of interest (20 to 200 μm).
2) The spatial distribution of the spray in the airflow within the tube should be as uniform as possible.
3) The spray should be injected into the airflow as close to the test section (heated portion of the duct) as possible.
4) The spray injection process should not materially disturb the airflow into which the spray is injected.
5) The liquid flow rate through a given injector should be controllable

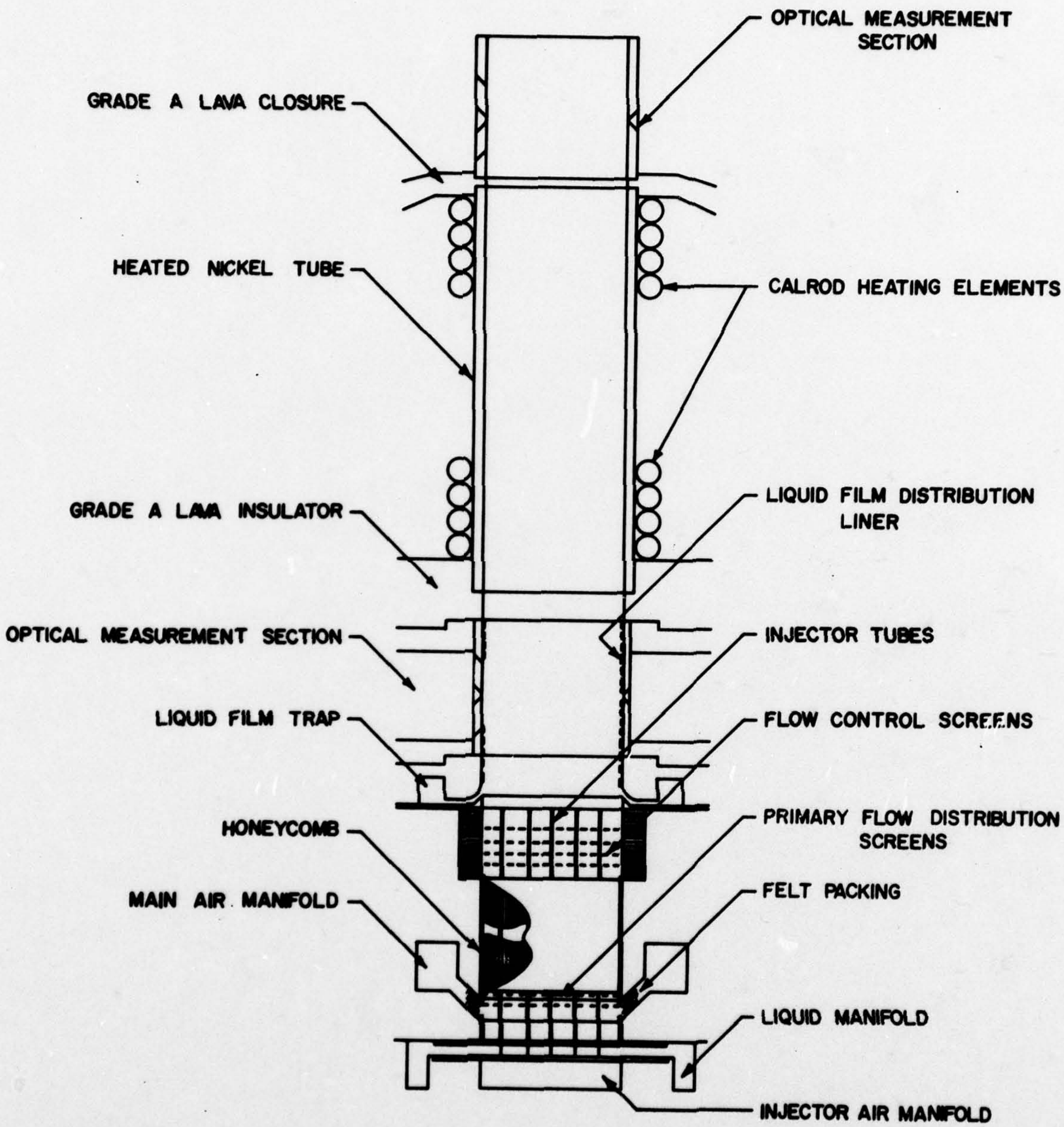

Figure 7. Experimental Apparatus for Ignition of Fuel Sprays by Hot Surfaces

over a reasonable range while maintaining separate control over the SMD of the spray created.

Given the low-velocity airflows of interest, these conditions were difficult to meet. Moreover, there is the need to establish symmetric and controlled airflow conditions in short distances, accommodating the liquid injection system and the fact that the dimensions of the liquid system in the flow direction could not be too large because of the excessive liquid pressure drops which would be required. This required special attention to tailoring the airflow distribution within the framework of the liquid system and subject to the limitations the geometry of the liquid system imposed. Insofar as can be assessed from the operating experience to date, the apparatus described here serves to meet most of the requirements outlined.

Injection System.

Because of the unusual requirements placed on the liquid injection system special attention was devoted to this problem at the outset of the research activities. The method of injection developed for this purpose was virtually dictated by the requirements. The first and last conditions, (1) and (5), virtually require at least partial use of air blast atomization methods, whereby the droplet sizes produced depend on the velocity of the shearing airflow. The need to introduce the spray into preset airflow conditions without a significant disturbance implicitly imposes the constraint that whatever airflow may be required for the atomization process, it must not be a significant portion of the total air flow rate. The second condition, together with the third, require the use of an array of injection points in the flow because the time required for distribution of sprays injected non-uniformly over the flow cross section could contribute materially to the fraction of fuel vaporized, a parameter which is to be controlled independently in the experiments (by employing air/vapor mixtures of varying composition in the bulk flow, for example).

The problem which appeared most troublesome was that raised by condition (4) above. Virtually all existing atomization/injection schemes in practical devices make use of methods which would result in significant disturbances of the flow into which the spray is introduced. Given this and the other constraints, the injection of the spray in the flow direction of a prepared air flow (controlled velocity profile, turbulence properties, etc.) was considered the only serious candidate. The possibility of passing the spray/air mixture through any kind of flow conditioning device (screens, etc.) downstream of the injection station was rejected as at least undesirable because of loss of the liquid through impact and collection on the device. To meet the given requirements, then, the injector would have to create and introduce the spray into the prepared airflow in such a manner as to leave minimum momentum flux decrement or excess within inches of the injection station.

All of the above considerations dictated the use of microscopic air jets for air blast atomization. The prototype designs tested made use of air jets approximately 50 μm in diameter. Smaller jets were also examined. A design was tested which had the appearance of meeting most of the requirements described above. Several prototypes of the design were fabricated and tested, each yielding comparable performance. A single injector element, for example, provided 1 to 2 cc/min. liquid flow with about 50 cc/ min. airflow. Under conditions where stoichiometric air/fuel mixtures are to be considered (as they are to be in the ignition studies), the air flow rate through the injector would be about 0.2 to 0.3 percent of the total air flow rate and about 4 percent of the fuel flow rate. Liquid (water) and air pressures in the tests were on the order of a few psig and up to 30 psig, respectively.

The momentum flux of the air jet alone in the absence of liquid flow would be about twice that of the bulk airflow at 1 fps bulk flow velocity, considering the air jets to be sonic. This may be substantially reduced by the acceleration of the liquid and shearing of the liquid interface by the jet, however. A limited number of measurements were made by means of a laser anemometer for the purpose of estimating the velocities within the spray produced by the injector when flowing into still air. In assessing these results, it should be kept in mind that a range of particle sizes were present such that the largest of these could not be expected to follow the flow. Moreover, a tracker was employed rather than a counter-type processor. Since the signal strength would be dominated by the largest of the particles present, the measurements would reflect the motion of these particles. It is this information which is of principal interest anyway. The data taken were mean readings under conditions where the tracker was locked in, but where appreciable fluctuations in the mean values were present. Velocities observed under conditions of 1 cc/min. water flow ranged from a maximum of 8-10 fps at a distance of 1 inch from the injector face to less than 1 fps some 5-6 inches from the injector. Measurements closer to the injector face showed lower velocities as might be anticipated because of the acceleration of newly formed droplets in that region. Measurements made under conditions of the lowest possible liquid flow rate (finest mist) were 50 to 100 percent higher at the same airflow conditions (22-25 psig source pressure). Lower source pressures for the airflow yielded values accordingly lower (16 psig source pressure yielded a velocity of about 5 fps at 1 inch from the injector face, for example). These measured values are within reasonable expectations for the decay of circular air jets, with some allowance for momentum exchange between the phases.

These measurements, together with other information(observed settling velocities of the largest particles and appearance of the mist in forward-scattered light) suggested the design of the prototype injector was within reasonable reach of meeting the requirements set forth for the design.

The prototype injector elements were fabricated using glass nozzles bonded in stainless steel tubing. This was considered at least unserviceable for the application because of the thermal environment and the potential for breakage in handling and assembly. A brief development program was undertaken to attempt fabrication of the small nozzles entirely of stainless steel. This effort proved successful to the point where the nozzles could be made quite accurately. The nozzles were formed on the ends of 27-gauge stainless steel hypodermic tubing by a swaging process. One element of the injector assembly employing these nozzles is illustrated in Fig. 8, a photograph of the nozzle adjacent to the head of a common pin is shown in Fig. 9, and several photographs of the spray produced are shown in Figs. 10 and 11.

The array of injector elements assembled for the initial experiments comprised 46 elements arranged in three concentric rings of 0.688, 1.281, and 1.781 inch diameters with a central element and 9, 18 and 18 elements in the respective radial locations. This particular choice of the positions for the injector elements yielded roughly equal flow areas of comparable lateral dimensions served by the elements, while maintaining a reasonable approximation to axial symmetry in the spray distribution. Manifolding of the array of injector elements was accomplished by employing two drilled

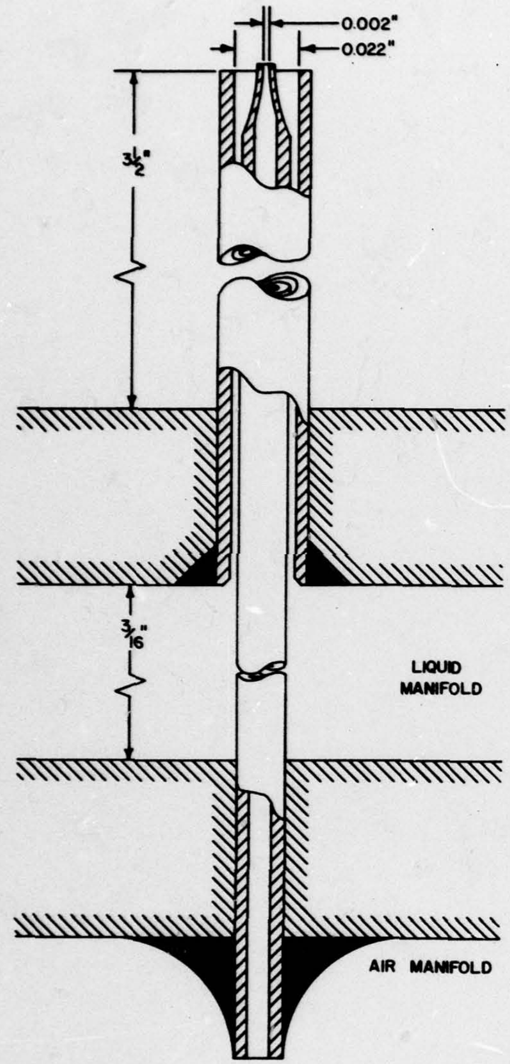

Figure 8. Typical Injector Element

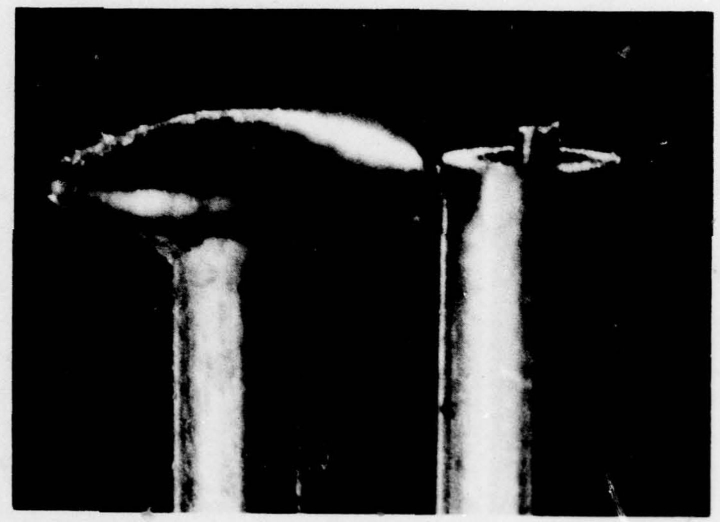

Figure 9. Photograph of an Injector Element Adjacent to the Head of a Common Pin

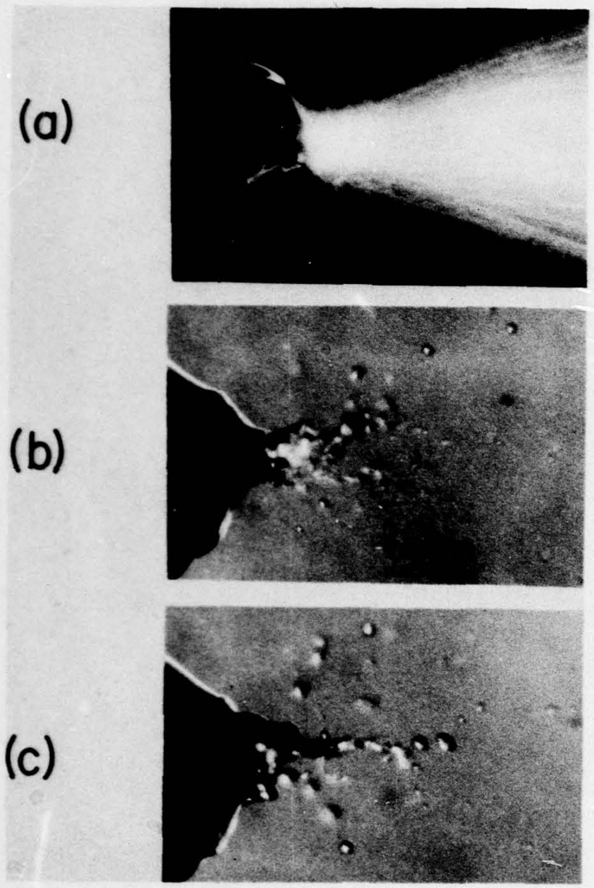

Figure 10. Photomicrographs of the Spray Produced by an Injector Element

Figure 11. Spray Pattern of an Injector Element

plates to which the tubes of the injector elements were soldered, one plate for the nozzle tubes and one for the outer liquid tubes. The dimensions of the elements and the plate separation are given in Fig. 8. The manifold plates were separated with 3/16-inch brass spacers. A photograph of the injector assembly is presented in Fig. 12. The honeycomb flow straightener for the main airflow and screens for airflow control are also shown in Fig.12 as they are mounted on the injector assembly. A photograph of the injector positioned in its manifold section, alongside the main air manifold section, is shown in Fig. 13. The screening in the liquid manifold helped reduce bubble entrapment and nonuniformities in the liquid distribution. Under conditions of equivalent stoichiometric fule/air mixtures, using water in place of the fuel, the spray patterns produced by this injector appeared to be acceptable. The discrete sprays appeared to coalesce within a couple of inches from the injection station, for example.

Control of the main airflow properties proved fairly straightforward (although time consuming). For example, referring to Fig. 7, it was found that suitable flow impedances were required (a) in the annular slot employed to introduce the air into the duct at the upstream end, and (b) in the plenum space upstream of the honeycomb straightener. Felt packing and an annular series of ports served to distribute the flow in an axisymmetric fachion, with, for example, a 10 psig pressure drop at a mean velocity of 35 fps in the 2-inch pipe. A series of screens of various meshes and separations were employed upstream of the honeycomb to distribute the air flow over the cross section of the duct. These were 16-mesh screens combined with layers of 100-mesh screening. By arranging these screens in various combinations and positions, it was possible to control the resulting velocity profile over a range from one with a sharp central peak to one with sharp peaks near the walls of the duct. It was quite difficult to avoid some level of flow distortion associated with clearance holes in the screens for the injector elements. Apart from that consideration, however, it does appear that ample control of the flow using upstream screens of the type tested is possible.

A honeycomb comprising a bundle of 15-gauge stainless steel tubes, 1 11/16 inches long, served as a flow straightener downstream of the flow conditioning screens. These tubes were bonded in a moderately tight array, subject to the

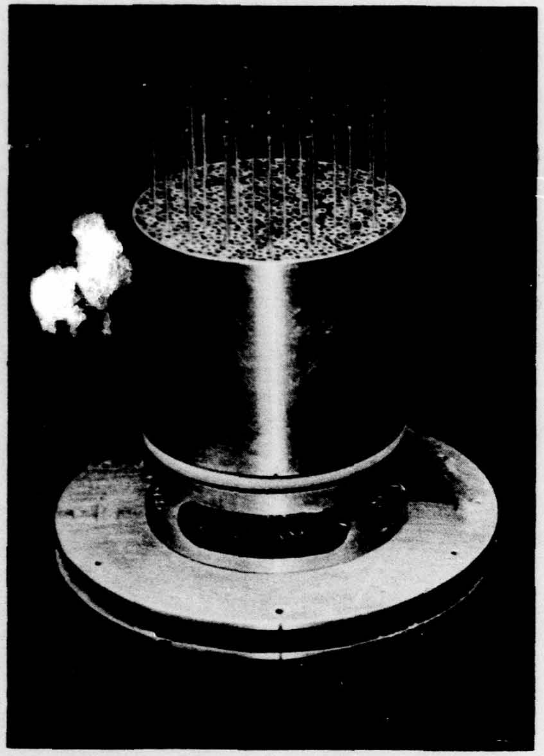

Figure 12. Injector Assembly

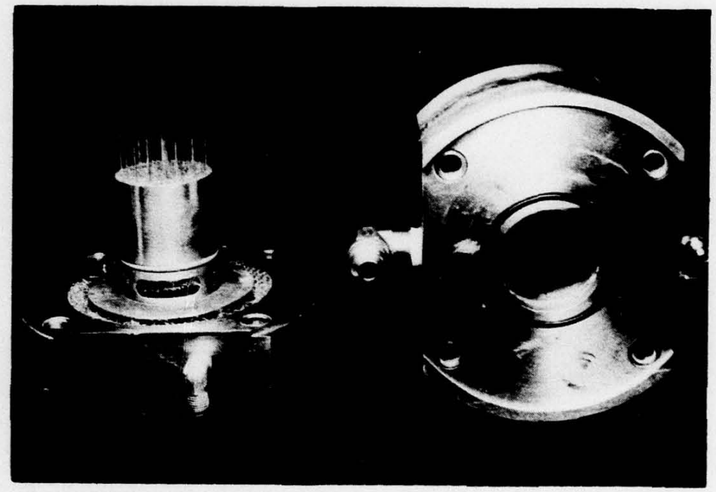

Figure 13. Injector Assembly, Injector Manifold and Air Manifold Sections

requirement that 46 of the tubes had to occupy the positions of the injector elements.

Provisions are made in the design for a set of flow control screens downstream of the honeycomb but upstream of the liquid injection station. It is intended that these screens (inconjunction with changes in the upstream screens, if necessary) be employed to tailor the mean velocity profile and the turbulence properties in the boundary layer region of the flow and in the free stream portion as well. From experience that has been gained in this regard, it appears that the major profile variations should be handled with upstream sereens, using the downstream screens for minor changes and for establishing particular turbulence properties.

Liquid Film Trap

The fact that some portion of the spray will impinge or diffuse to the walls of the duct downstream of the injector station but upstream of the heated tube required some provision for handling the liquid deposited on the wall. The formation of large droplets on the wall would, of course, have a detrimental and unpredictable effect on the boundary layer flow and the larger droplets may be broken up and partially entrained in the form of large droplets or streamers in the boundary layer flow. A means for handling this problem was devised (a) to disperse the liquid on the wall, and (b) to collect and remove it, possibly enabling measurement of that part of the rate of liquid loss from the main flow by that mechanism. The walls of the film trap and measurement sections were covered with a thin layer of 16-mesh copper screening to disperse the liquid by capillary action and a wick arrangement at the lower end of the film trap section served to collect the liquid for measurement. The liquid conveyed by the wick may be evaporated under vacuum conditions and subsequently condensed for measurement.

It was felt the material used to line the wall of the duct should not present too large an extended surface so as to yield an inordinate amount of vapor in the flow near the wall. Rather, the coarsest structure which would disperse the liquid droplets to form a thin film was preferred. This introduced a fixed level of wall roughness which will no doubt be reflected in the properties of the boundary layer entering the heated section of pipe.

For turbulent layers, which are of principal concern here, this may be expected to enhance transport phenomena near the wall, of course. The liner material may be changed, and it is planned to examine its influence on ignition results. For example, fine-mesh screening or a fibrous filter material may be utilized. In any event, some liner material must be used.

Measurement Sections

The measurement section for the measurement of the flow properties upstream of the heated tube is provided with two pairs of ports at 90° to each other. Each pair of ports comprises one port shaped in the form of a pair of crossed slits and a small circular aperture in the opposite wall of the tube. The slit widths and the aperture diameter were 1/16 inch. The lengths of the slits were chosen to accommodate the pair of laser beams from the LDA instrument (250 mm lens, 50 mm beam separation), when focused at the far wall, and the slit width would pass the focused beams without measurable scattering. The crossed slits accommodate measurements of the streamwise components of velocity and the lateral component (for turbulence measurements) with minimal disturbance of the flow either in the vicinity of the measurements (near the wall with the circular aperture) or at the opposite wall. It was anticipated that windows and purge arrangements might be required, but the evidence to date suggests there will be no need for closures on these ports.

A similar section is provided for the measurements downstream of the heated tube.

Heated Pipe Section

A 6-inch length of 2-inch, Schedule 40 nickel pipe is to serve as the heated section for the initial research activities. Two CALROD heater units, formed on the outside of the pipe in tight helical coils, one at each end, are employed for heating the pipe. Insulation is provided by blocks of Grade A Lava situated around the assembly. A stainless steel sheath encloses the entire unit. Power for the heaters is provided through a pair of 60-amp VARIAC circuits.

Gas Flow Systems

Four gas systems were installed to serve the needs of the experimental investigation. Referring to Fig. 14, they comprise the main air system, the injector air system, the ejector air system and the nitrogen system. The nitrogen system provided a regulated source pressure of 300 psi for control purposes and also supplied nitrogen for the purpose of purging the injector following runs with fuel. Air for all of the air systems was drawn from the high-pressure laboratory air line (2200 psi) through a 5-micron filter. The main air system was provided with two separate orifice-type flowmeters for covering the range of flow rates anticipated for the research. The ejector system was installed to dilute, cool and discharge the fuel/air or water/air mixtures from the test cell. Two six-element arrays of supersonic nozzles were placed at the upstream ends of the two principal legs of the ejector piping ($3\frac{1}{2}$-inch pipe). This system has been found to serve the purpose quite well. The maximum design pressure for the ejector nozzles was 300 psi; for most conditions, however, lower pressures suffice. Detailed component listings for the system may be found in the Appendix.

Liquid Flow Systems

Liquid flow systems were installed to provide water and fuel for the research. Referring to Fig. 15, both systems made use of variable-displacement metering pumps capable of operation up to 160 psi. The water system included a deionizer, a coarse (25 micron) filter and a fine (3 micron) filter, and provisions for by-passing the injector system without shutting down the flow. The water in the inlet line to the pump was maintained at a few psi by means of a continuous bleed arrangement fed from the laboratory water line. The fuel system incorporated a 300-gallon tank located outside the laboratory. Fuel from the tank was pumped by a circulating pump into the laboratory where the fuel passed through a heat exchanger, bringing the fuel temperature nominally up to that of the laboratory water supply. As in the water system, the fuel pressure at the inlet side of the metering pump was maintained at a few psi. Both liquid systems employed accumulators for reducing fluctuations in the liquid flow rate, and both were metered using ball-type flowmeters. Detailed component listings for the systems may be found in the Appendix.

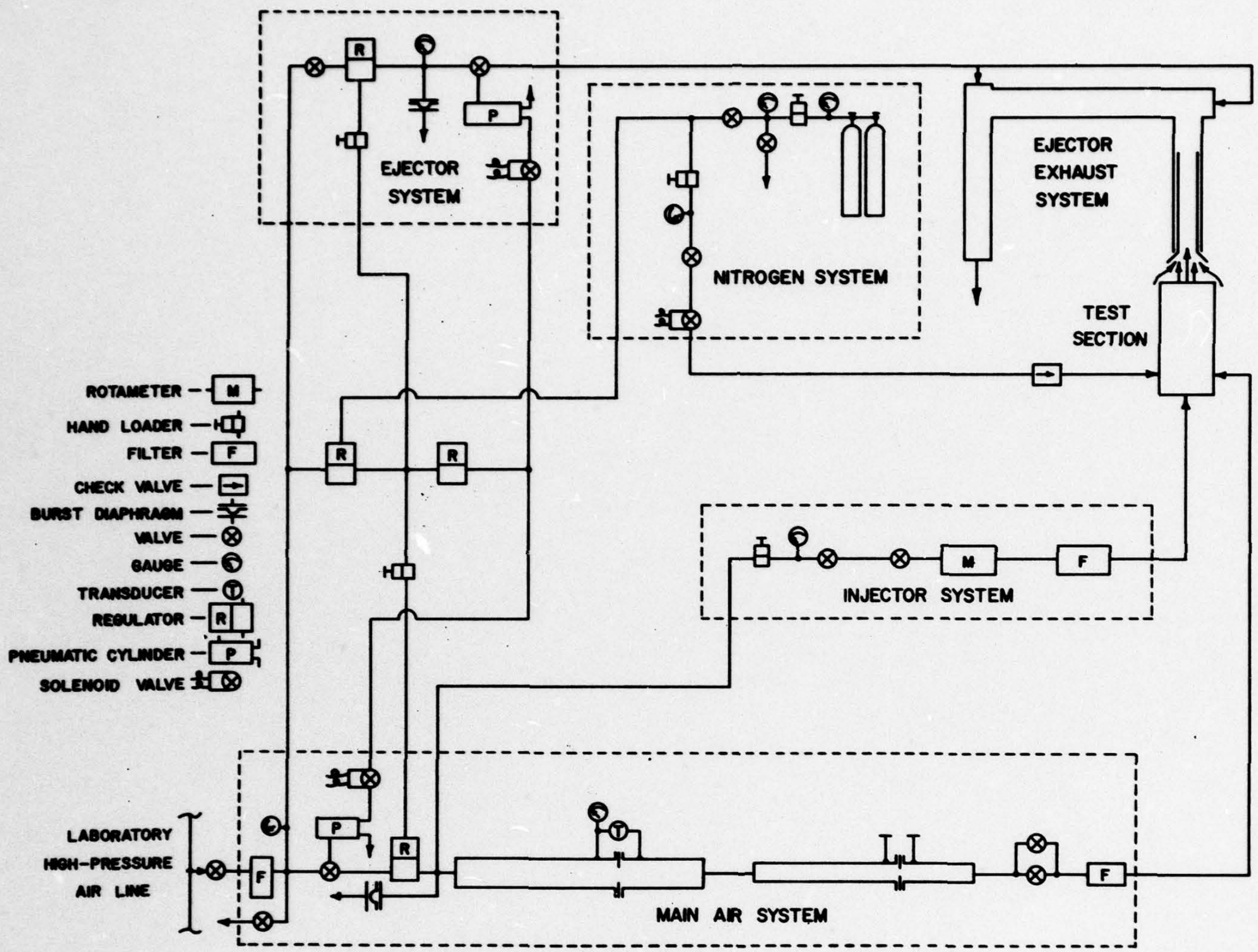

Figure 14. Gas Supply Systems

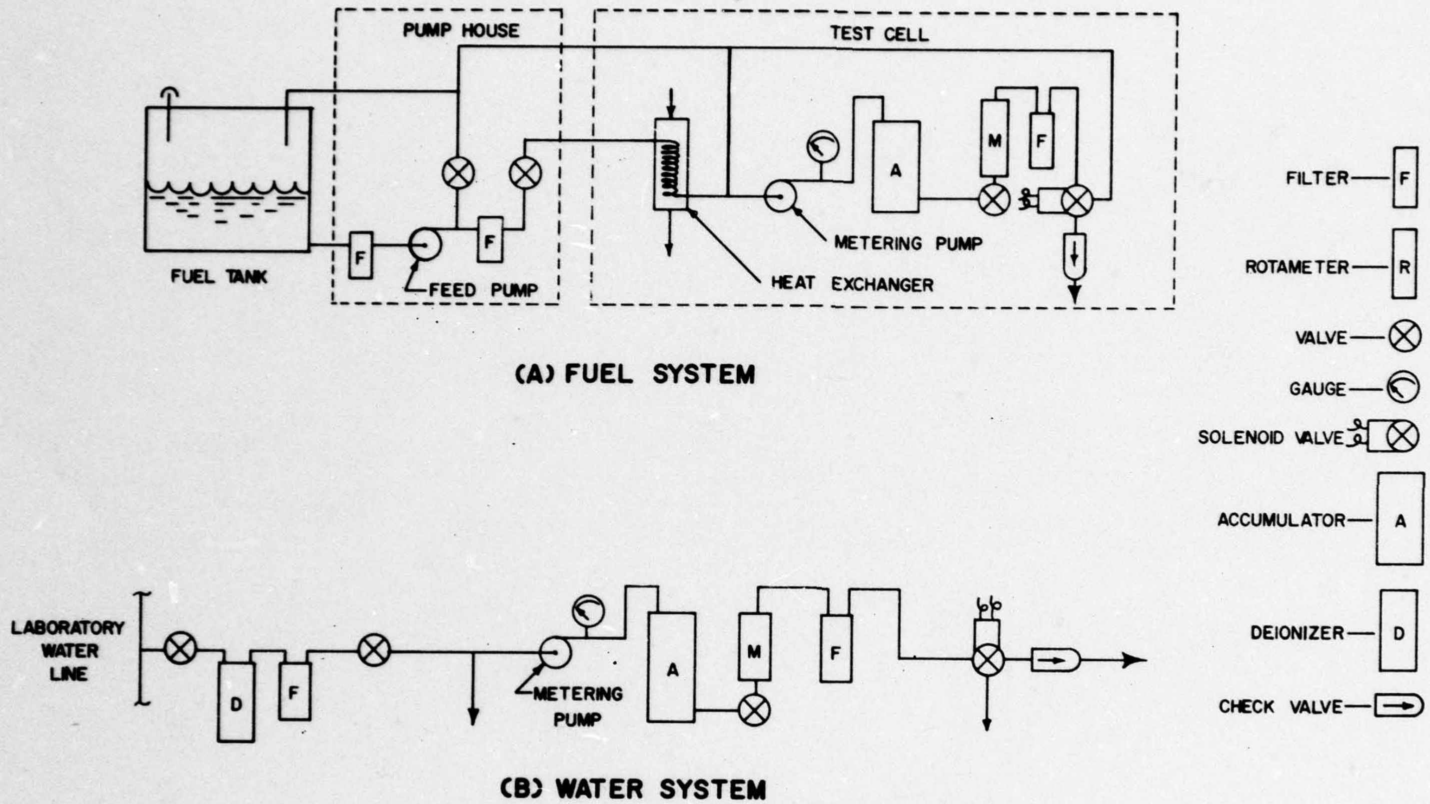

Figure 15. Liquid Supply Systems

Electrical Systems

Six principal power circuits were arranged to handle the electrical needs of the experiments. They are as follows.

a) Laser Power Circuit. (240v, 3-phase, 35 amps, drawn from main laboratory 3-phase buss at primary switch panel, with fused switch in the test cell)

b) 2 CALROD Heater Power Circuits. (240v, 1-phase, 60 amps each, drawn from utility buss duct in laboratory, with separate fused switches in test cell)

c) 2 Utility and Instrument Power Circuits. (115 v, 1-phase, 30 amps each, drawn from cell power outlets)

d) D.C. Power Circuit. (24v.d.c., from laboratory d.c. circuit, switched outside test cell)

Measurements

Measurements to be made in the research may be divided into two groups: 1) those of a routine character made for each run and related to the basic system, and 2) those related directly to properties of the spray or to the airflow in the test section of the apparatus. A listing of measurement components is provided in the Appendix.

Measurements related to the basic system include the following.

Pressure. Upstream orifice pressure for main airflow.
Orifice pressure differential for main airflow.
Injector air supply pressure.
Purge nitrogen supply pressure.
Ejector supply pressure.

Temperature. Downstream air temperature in the orifice meter for the main air flow.
Air temperature in the main air manifold.
Air temperature in the injector air manifold.
Liquid temperature in the injector liquid manifold.
Wall temperatures in the heated pipe section.

Flow Rates. Main air.
Injector Air.
Liquids (water and fuel).

Pressure measurements are made with either bourdon-type gauges or strain-gage transducers or both. Temperature measurements are made with Type K (Chromel/Alumel) thermocouples. And the liquid flow rates are measured with ball float-type flowmeters. Nominal accuracies for most of these measurements are 2 percent or so at best.

Measurements related directly to the properties of the spray or the airflow in the test section include primarily the following.

Pitot pressure measurements of the airflow in the absence of the spray (oil-filled micromanometer).

Laser velocimeter measurements of the droplet velocities. (TSI system, Spectra Physics laser).

Laser scattering measurements for droplet sizes (SMD, size distribution, etc.)

Sampling probes for fraction of fuel vaporized, enthalpy measurements, fuel distribution, chemical composition.

The LDV system may serve both for velocity and local particle size measurement purposes. A Tektronix Model 7834 storage-type oscilloscope with 200 MHz preamps and a local minicomputer will be available for signal analysis purposes. The sampling probes will either be heated or of a special design with provisions for drawing off liquid condensate from the outer surfaces of the probes to prevent formation of large droplets.

A photograph of the control and measurement console is shown in Fig. 16.

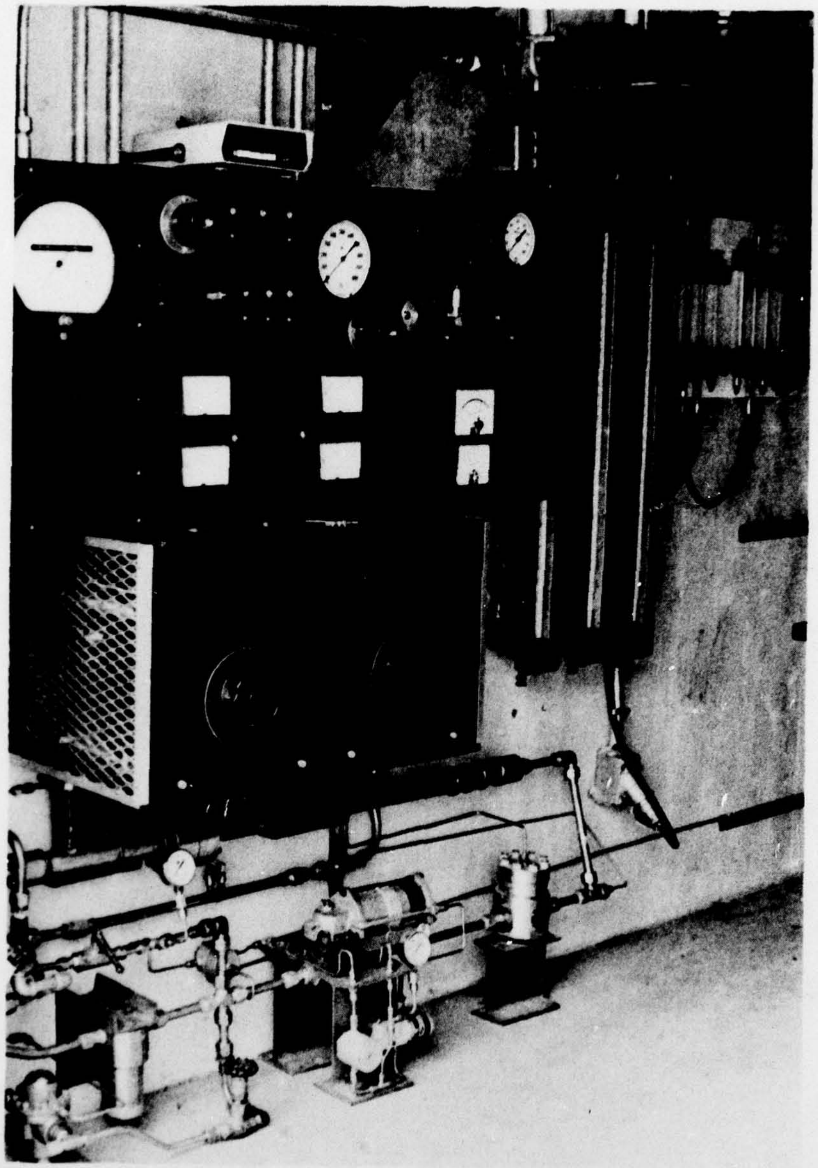

Figure 16. Control and Measurement Console

III. COMBUSTION TUNNEL FOR FLAME STABILIZATION RESEARCH

A combustion tunnel suitable for the research on flame stabilization has been installed in this laboratory by the School of Mechanical Engineering. The tunnel is fed by a large fan unit comprised of two Type CB pressure fans supplied by the Buffalo Forge Company. The system is capable of supplying 10 lb/sec at 3.25 psig. The fan unit feeds a duct system terminating in three independent test sections, one of which is to be employed for the subject research activity.

The experimental requirements for this part of the investigation call for the capability of heating the airflow. That is to be done by combustion in a chamber utilizing a conventional gas turbine combustor can. Air temperatures up to 500 ^{o}K should be attainable with the design adopted. Spray injection systems for both fuel and water are to be fabricated and installed in the ducting of the combustion tunnel upstream of the test section. The test section and all hazardous systems involving the fuel/air mixture are to be located in one of two large test cells designed for that purpose. The system may be operated remotely as required for safety reasons, when necessary.

A schematic diagram of the test section ducting is presented in Fig. 17. The transition section illustrated in Fig. 17 essentially serves three purposes: (i) it provides a sufficient flow length for the mixing of auxiliary hot gas and the cold mainstream, (ii) it provides enough residence time for complete evaporation of the fuel sprayed into the mainstream, and (iii) it provides enough time for the mixing and evaporation of water injected into the mainstream. Fuel injectors of the Delevan type pressure swirl atomizers are employed as indicated in Fig. 17. The transition section, then, delivers a uniform mixture of air plus fuel and water vapor to the test section.

The test sections are 1 ft square ducts of lengths 1/2, 1, and 1.5 ft, as shown in Fig. 18. This duct is fitted with ports for introducing thermocouple and pitot probes for appropriate traverse measurements. The flameholders will be mounted as shown in Fig. 17.

Three types of flameholders have been fabricated for the investigations. Referring to Fig. 19, the initial runs will be made with flameholders of the following dimensions.

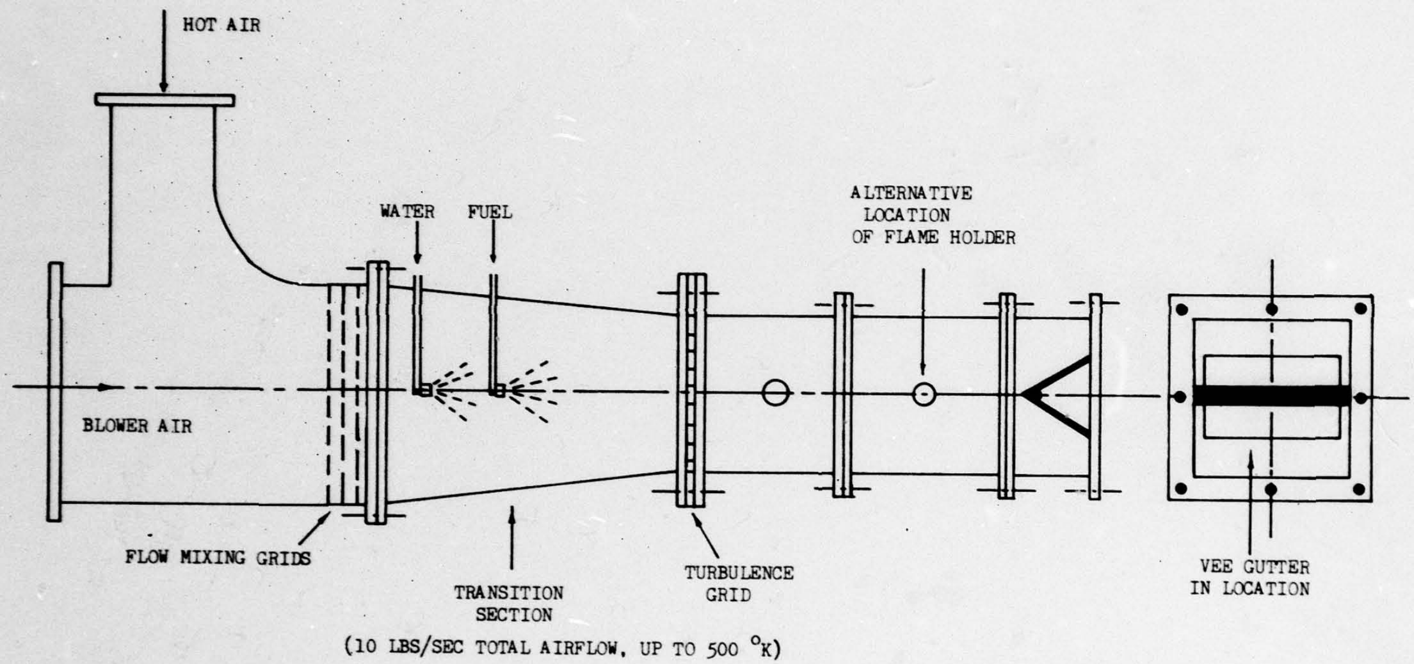

Figure 17. Schematic Diagram of the Test Section in the Combustion Tunnel

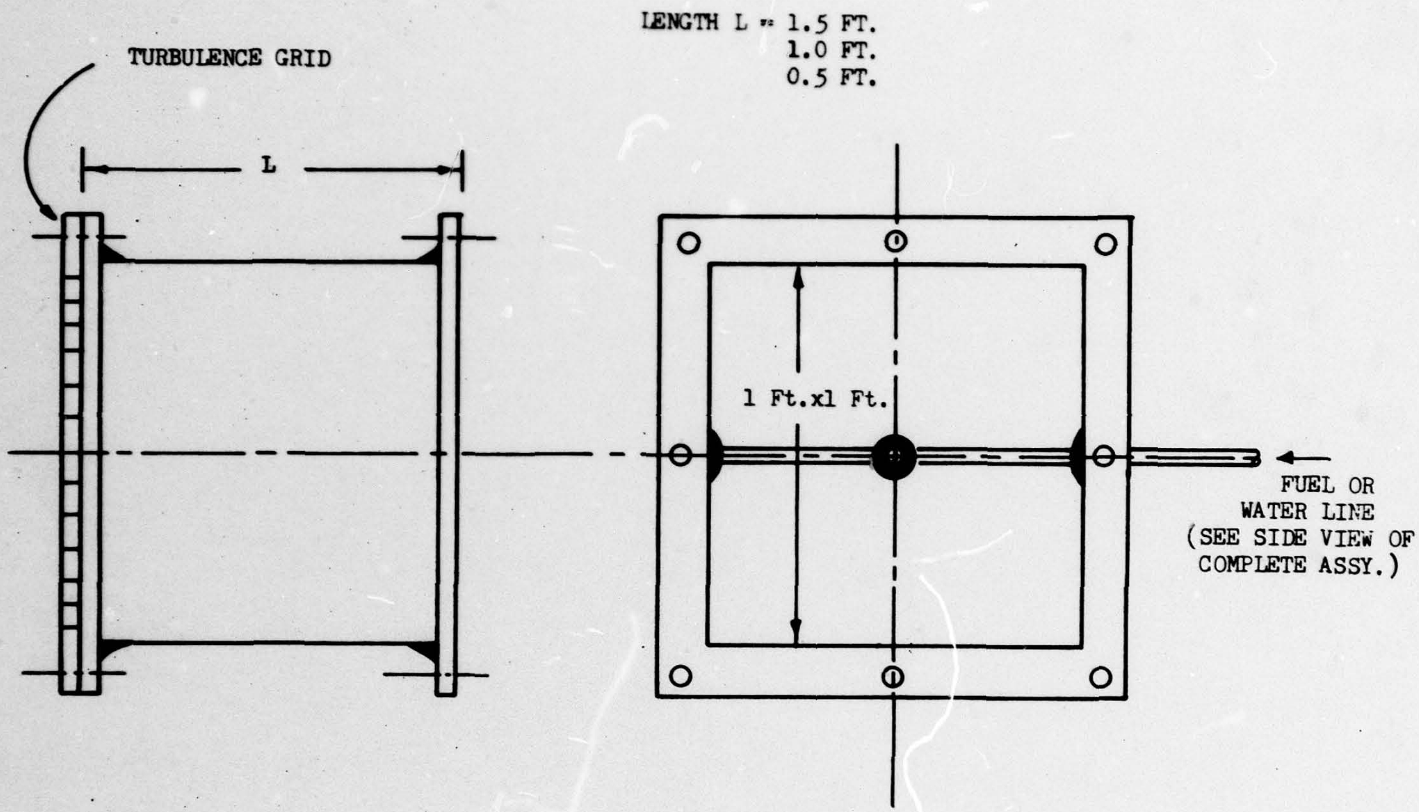

Figure 18. Test Section

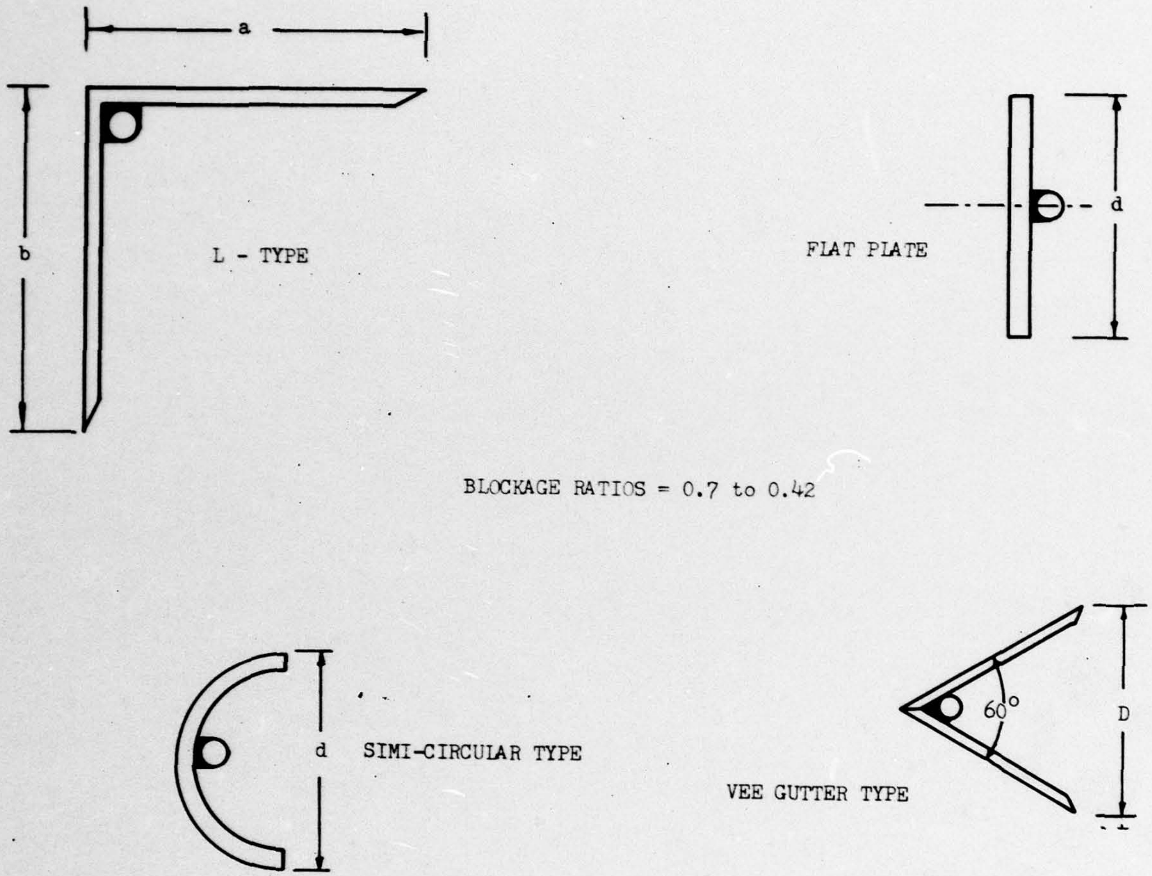

Figure 19. Flame Stabilizer Geometries

Flameholder/Blockage Ratio		0.42	0.28	0.14	0.07
(a) V-gutter type	d =	6"	4"	2"	1"
(b) L-gutter type	a = b =	6"	4"	2"	1"
(c) C type (or flat plate)	d =	6"	4"	2"	1"

These will provide a range of sizes, shapes, and blockage ratios. As mentioned in the INTRODUCTION the experiments will be conducted both with and without blockage effects - that is, both within the duct and in an "open jet" configuration of the tunnel. Kerosene (Jet-A) will be employed in the experiments.

The ductwork, the flameholders, and fuel and water supply systems have been fabricated for this research. Preliminary runs have been undertaken.

IV. DISCUSSION

The experimental facility for spray ignition research has been operated for some months, now, and on the basis of our experience with it, the arrangement appears to be a satisfactory one in most respects. Some further efforts will be required to refine the flow profiles for each run condition, of course, and the provisions for purging the injector with nitrogen are to be modified slightly to reduce the void volume in the system after purging. The latter is to improve the response time of the liquid flow systems. Some minor modifications in the original mechanical design of the system will also be made to facilitate maintenance and cleaning of the injector nozzles, for example. The ejector exhaust system functions well, but it was found there was appreciable ice formation on the ejector nozzles when operating with water sprays during colder weather (lower ejector air temperatures). This may require heating the ejector air for operation over extended periods (hours).

Preliminary experiments were conducted employing a heated cylindrical rod with its axis normal to the flow direction and situated just above the first measurement section (the heated pipe was removed for these runs). Stoichiometric mixtures of JP-4 and air at approximately 10 fps were ignited in the experiments. The ignition was found to be smooth and repeatable at rod temperatures of approximately 1300 ^{o}F (705 ^{o}C). Following ignition, the flame appeared to stabilize at the downstream face of the measurement section before it was extinguished by suddenly increasing the air flow rate. These experiments suggested the 6-inch length of heated pipe should be more than ample for the ignition study and showed that blowoff could be employed for flame extinction without damage to the components of the apparatus. Some further ignition experiments of a preliminary character are in progress and the detailed measurements of the flow properties are being undertaken.

The combustion tunnel components for flame stabilization research are in place, including the test section, flame stabilizers, fuel and water systems, etc. Preliminary calibration runs have been undertaken and final testing should be underway soon.

APPENDIX

Component Listings

Nitrogen System	
Regulator	Grove Model 94
Hand Loader	Grove Model 15L
Solenoid Valve	Marotta Model MV100
Manual Valves	Hoke
Pressure Gauges	Hoke (0-3000 psi), Mathesson (0-1000 psi) Weiss (0-160 psi)
Check Valve	Circle Seal
Main Air System	
Primary Filter	Fluid Dynamics Model 3067, 5μ element
Main Pneumatically Actuated Valve	Jamesbury, Model ST20MS cyclinder, 1-inch, 3000 psi ball valve
Regulator	Grove Model 212B
Hand Loader	Grove Model 15L
Burst Diaphragm	Black, Sivalls & Bryson, 1/2-inch union housing
Secondary Filter	3/4-inch Microporous Filter, Annaheim, CA, 10μ element
Pressure Gauge	Heise (0-500 psi)
Pressure Transducer	Statham Model 5112 (0-100 psid)
Pilot Valve	Marotta Model MV 543H
Injector Air System	
Hand Loader	Honeywell (0-30 psi)
Flowmeter	Gilmont Model 3202
Filter	Circle Seal, 10μ sintered element
Pressure Gauge	Duragauge (0-30 psi)
Ejector Air System	
Regulator	Grove Model 202G
Hand Loader	Grove Model 15LH
Pneumatically Actuated Valve	Jamesbury, 1-inch ball valve
Solenoid Valve (Pilot)	ASCO 8345A5
Burst Diaphragm	Black, Sivalls, & Bryson, No. 77-24
Pressure Gauge	Duragauge (0-1000 psi)
Fuel System	
Tank	300 gal
Metering Pump	March Model 210-10R
Flowmeter	Gilmont Type 3203
Primary Filter	Filterex, 10-inch, Model IPAI-3/4 with 25μ element
Secondary Filter	10-inch housing, 3 μ element
Solenoid Valve	ASCO Model 8320A172
Check Valve	Circle Seal

Water System	
Metering Pump	March Model 210-10R
Deionizer	Barnstead Model 00807
Primary Filter	Filterex, 10-inch, Model IPAI-3/4 with 25µ element
Secondary Filter	Filterex, 10-inch, Model IPAI-3/4 with 5µ element
Flowmeter	Gilmont Type 3203
Solenoid Valve	ASCO Model 8320A172
Check Valve	Circle Seal
Electrical System	
Variacs (2 units)	General Radio Model W50HG2BB, 240v, 50a.
Measurement Systems	
Laser Velocimeter Components	TSI, Inc.
Counter Processor	Models 1994, 1985, 1992, 1998
Transmitting Optics	Model 910
Receiving Optics	Model 940
Polarization Rotator	Model 901
Beam Collimator	Model 908
Laser	Spectra Physics Model 164 argon ion laser with Model 265 power supply
Oscilloscope	Tektronix Model 7834 with Type 7A24 preamps, Type 7B85 & 7B80 time bases
Microcomputer	PDP 1103 series or equivalent
Vacuum System	Low Density Flow Facility: 3000 cfm at 1 torr with 10,000 cu. ft. reservoir.
Combustion Tunnel Components	
Fan	Buffalo Forge, Duplex, Type CB
Fuel Pump	Madden Model M-1000, 550 gph at 30 psi
Flowmeter	Brooks Series 4900, 5/8-inch, 55-550 gph
Fuel Nozzles	Delevan

REFERENCES

1. Faeth, G.M., "Current Status of Droplet and Liquid Combustion," paper presented at the Central States Meeting of the Combustion Institute, Cleveland, (Mar., 1977).

2. Osgerby, I.T., AIAA J., 12, 743 (1974).

3. Odgers, J., 15th Symp. (Int.) on Combustion, Tokyo, Japan, 1321 (1974).

4. Williams, A., Combustion and Flame, 21, 1 (1973).

5. Patil, P.B., et al., "Analysis of Spray Combustion in a Research Gas Turbine Combustor," paper presented at the Central States Meeting of the Combustion Institute, Cleveland, O., (Mar., 1977).

6. Yang, C.H., "Droplet Spray and Particle Cloud Combustion," in NASA CR-134744 by Berlad, et al., (1974).

7. Law, C.K., "Analysis of Thermal Ignition Lag in Fuel Droplet Combustion," paper presented at the Central States Meeting of the Combustion Institute, Cleveland, O., (Mar., 1977).

8. El-Wakil, M.M. and Abdou, M.I., Fuel, 45, 177 (1963).

9. Faeth, G.M. and Olson, D.R., SAE Trans., 77, 1793 (1968).

10. Haber, F. and Wolff, H., "Mist Explosions," Z. Angew. Chem., 36, 373 (1923).

11. Burgoyne, J.H. and Richardson, J.F., Fuel, 28, 2 (1949).

12. Burgoyne, J.H. and Cohen, L., Proc. Roy. Soc., A225, 375 (1954).

13. Burgoyne, J.H., Chem. Eng. Prog., 53, 121-M (1957).

14. Burgoyne, J.H. and Newitt, D.M., Trans. Inst. Marine Engrs., 67, 255 (1955).

15. Jones, G.W., "Research on the Flammability Characteristics of Aircraft Fuels," WADC Rept. 52-35 (June, 1952).

16. Browning, J.A. and Krall, W.G., "Effects of Fuel Droplets on Flame Stability, Flame Velocity, and Inflammability Limits," Project SQUID Tech. Rept. No. DART-4-P (Sept., 1954).

17. Mullins, B.P., "Flammability of Heterogeneous Fuel-Air Mixtures," Chap. XII in Explosions, Detonations, Flammability and Ignition, ed. by S.S. Penner and B.P. Mullins, Pergamon Press, N.Y. (1957).

18. Ballal, D.R. and Lefebvre, A.H., "Ignition of Liquid Fuel Sprays at Subatmospheric Pressures," paper presented at the Central States Meeting of the Combustion Institute, Cleveland, O., (Mar., 1977).

19. Subba Roa, H.N. and Lefebvre, A.H., Comb. Sci. and Tech., 8, 95 (1973).

20. Rao, K.V.L. and Lefebvre, A.H., Combustion and Flame, 27, 1 (1976).

21. Rao, K.V.L., "Spark Ignition Studies in Flowing Liquid Fuel-Air Mixtures," Ph.D. Thesis, Cranfield Institute of Technology (1974).

22. Ballal, D.R. and Lefebvre, A.H., Combustion and Flame, 24, 99 (1975).

23. Ballal, D.R. and Lefebvre, A.H., 15th Symp. (Int.) on Combustion, 1473 (1974).

24. Frank-Kamenetski, Diffusion and Heat Exchange in Chemical Kinetics, transl. by N. Thon, Princeton U. Press (1955).

25. Semenov, N.N., Chemical Kinetics and Chain Reactions, Oxford U. Press, London (1935).

26. Lewis, B. and von Elbe, G., Combustion, Flames and Explosion of Gases, Academic Press, N.Y. (1951).

27. Jost, W., Explosion and Combustion Processes in Gases, McGraw-Hill, N.Y. (1946).

28. Penner, S.S. and Mullins, B.P., Explosions, Detonations, Flammability and Ignition, Pergamon Press, N.Y. (1957).

29. Silver, R.S., Phil. Mag., 23, 633 (1937); Patterson, S., Phil. Mag., 28, 1 (1939).

30. Mullins, B.P., Fuel, 32, 234 (1953).

31. Marble, F.E. and Adamson, Jr., T.C., Jet Propulsion, 24, 85 (1954).

32. Dooley, D.A., "Combustion in Laminar Mixing Regions and Boundary Layers," Ph.D. Thesis, Caltech (1956).

33. Glendenning, W.G. and Drinkwater, J.W., J. Roy. Aeron. Soc., 51, 616 (1947).

34. Simmons, H.C., "The correlation of Drop-Size Distributions in Fuel Nozzle Sprays: Pt. I, The Drop-Size/Volume Fraction Distribution," ASME Paper 76-WA/GT-9 (Dec., 1976).

35. Simmons, H.C., "The Correlation of Drop-Size Distributions in Fuel Nozzle Sprays: Pt. II, Drop-Size/Number Distribution," ASME Paper 76-WA/GT-10 (Dec., 1976).

36. Foster, M.M. and Ingebo, R.D., "Evaporation of JP-5 Fuel Sprays in Air Streams," NACA RM 55K02 (1956).

37. Rao, K.V.L. and Lefebvre, A.H., Combustion and Flame, 26, 303 (1976).

38. Bahr, W., "Evaporation and Spreading of Isooctane Spray in High Velocity Air Streams," NACA RM E 53I14 (1953).

39. Shapiro, A.H. and Erickson, A.J., Trans. ASME, 79, 775 (1975).

40. Sirignano, W.A. and Law, C.K., "A Review of Transient Heating and Liquid-Phase Mass Diffusion in Fuel Droplet Vaporization," Symp. on Evaporation-Combustion of Fuel Droplets, San Francisco (Aug., 1976).

41. Haarje, D.T. and Reardon, F.H., eds.,"Liquid Propellant Rocket Combustion Instability," NASA SP-194 (1972).

42. Chigier, N., "Instrumentation Techniques for Studying Heterogeneous Combustion," paper presented at the Central States Meeting of the Combustion Institute, Cleveland, O. (Mar., 1977).

43. Bernard, J.M. and Penner, S.S. "Determination of Particle Sizes in Flames from Scattered Laser Power Spectra," AIAA Paper 76-207 (Jan., 1976).

44. Sinclair, D. and LaMer, V.K., Chem. Rev., 44, 245 (1949).

45. Scurlock, A.C., "Flame Stabilization and Propagation in High Velocity Gas Streams," Project Meteor Rept. 19, Mass. Inst. of Technol. Fuels Research Laboratory, 1948.

46. Spalding, D.B., "Theoretical Aspects of Flame Stabilization." Aircraft Engineering, 25, 264 (1953).

47. Lefebvre, A.H., "Theoretical Aspects of Gas Turbine Combustion Performance," College of Aeronautics Note, Aero No. 163, 1966, Cranfield Institute of Technology.

48. Barrere, M. and Mestre, A., Selected Combustion Problems I, Butterworths, (1954), p.426.

49. Mestre, A., Combustion Researches and Reviews, AGARDograph 9, Butterworths, (1955), p. 72

50. Longwell, J.P., et al., Third Symposium on Combustion, Flame and Explosion Phenomena, Williams and Wilkins, (1949), p. 40

51. Longwell, J.P., et al., Ind. Eng. Chem., 45, 1629 (1953).

52. Lefebvre, A.H., "A method of predicting the aerodynamic blockage of bluff bodies in a ducted airstream," College of Aeronautics Rept. Aero. No. 188, 1965, Cranfield Institute of Technology.

53. Jeffs, R.A., Eighth Symposium (Int.) on Combustion, Williams and Wilkins, 1962, p. 1014.

54. Zukoski, E.E., and Marble, F.E., Proc. of the Gas Dynamics Symposium on Aerothermochemistry, Northwestern Univ., 1956, p. 205.

55. Strehlow, R.A., Fundamentals of Combustion, International Textbook Co., Scranton, Pa., (1968), pp. 267-8.

56. Williams, G.C., Hottel, H.C., and Scurlock, A.C., Third Symp. on Combustion, Flame and Explosion Phenomena, Williams and Wilkins, (1949), p. 21.

57. Longwell, J.P., Frost, E.E. and Weiss, M.A., Ind. Eng. Chem., 45, 1629 (1953).

58. Mullins, B.P., Combustion Researches and Reviews, AGARDograph 9, Butterworths, (1955), p. 87.

59. Spalding, D.B., Some Fundamentals of Combustion, Academic Press, N.Y. (1955), p. 185.

60. Zukoski, E.E. and Marble, F.E., Proceedings of the Gas Dynamics Symposium on Aerothermochemistry, Northwestern Univ. Ill., (1956), p. 205.

61. Khitrin, L.N. and Goldenberg, A.A., Sixth Symp. (Int.) on Combustion, Reinhold, (1957), p. 545.

62. Cheng, S.L. and Kovitz, A.A., Seventh Symp. (Int.) on Combustion, Butterworths, (1959), p. 681.

63. Loblich, K.R., Ninth Symp. (Int.) on Combustion, Academic Press, (1963), p. 949.

64. Lefebvre, A.H. and Halls, G.A., AGARD Advanced Aero Engine Testing, Pergamon Press, N.Y. (1959), p. 177.

65. Clodfelter, R.G., "Vulnerability of Dry Bays Adjacent to Fuel Tanks under Horizontal Gunfire," AFAPL-TR-72-83, (Mar., 1973).